UR-1571
Nov 1999

Pseudo-Dirac Neutrinos

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Abstract

We propose a scheme in which a pseudo-Dirac structure for three family of light neutrinos is generated naturally. An extended Higgs sector with a majoron is used for the generation of the leptonic number violating neutrino Majorana mass. The resultant neutrino mass matrix could easily fit all available experimental data. We discuss relevant constraints on the scales involved for the model to be phenomenologically viable.

Typeset using REVTEX

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Introduction. It is well known that the fermion spectrum of the Standard Model (SM) exhibits a three-family structure with a strong hierarchy of masses among them. In the quark sector, this has been taken as an indication of hierarchical mass matrices with small mixing among the families, as for example discussed in Ref. [1]. The charged lepton masses show the same hierarchy, while no physical mixing parameters can be introduced without first giving masses to neutrinos, which cannot happen within the SM.

Recently, experimental data on atmospheric and solar neutrinos strongly suggest the existence of neutrino masses and oscillations [2–4]. Furthermore, taking seriously all the available experimental data altogether suggests the existence of more than three light neutrinos [5]. As indicated by the atmospheric neutrino oscillation data [3], if there are only three active neutrinos, as in the SM, a different kind of family mixing or flavor structure would be implied [6–8]. In particular, the mixing angle that is responsible for the atmospheric neutrino oscillation is determined to be maximal. It is also very likely that the mixing angle that is responsible for the solar neutrino deficit is also nearly maximal, be it large angle MSW resonant oscillation solution or vacuum oscillation. This naturally poses a puzzle : why are neutrino family hierarchy so different from that of the quarks or the charged leptons? Indeed, there are many papers in the literature that address this disparity in the hierarchical structures. Some works within three active family framework and use intricate lepton family symmetries or quantum correction to generate the new hierarchy in the neutrino sector. Alternatively, one can introduce the right-handed neutrinos (in parallel with the quark and charged lepton sectors) and use the fact that lepton number can be broken uniquely in the neutrino sector to blame the new hierarchy on the related Majorana masses of the right-handed neutrinos. In that case the Dirac masses may still enjoy the same hierarchy as the quark and charged lepton sectors. This actually may be a more practical approach toward the various problems facing particle physics. It is commonly recognized that family hierarchy problem is very tough to elucidate. This approach allows one to decouple the family hierarchy problem with some of the problems related to neutrino oscillations such as the smallness of neutrino masses and the maximal character of some of the mixing angles. Furthermore, another hint that support this picture of neutrino mass pattern is the the data from LSND [4] which suggests that the muon neutrino mixes with some other neutrino with a mixing angle the size of the cabibbo angle. This would follow from the current picture if the Dirac masses of the neutrino have the same hierarchical structure as that of the quarks and charged leptons.

Three families of right-handed neutrinos is a common feature of many extensions of SM, in an $SO(10)$ unification framework or otherwise [9]. Among the extension of SM with right-handed neutrinos, the most popular ones incorperate the so-called “seesaw” structure, which naturally explain the smallness of the neutrino masses by invoking a high intermediate or GUTs scale. However, unless the issue is coupled with the fermion hierarchy problem, this approach does not naturally explain why some of the oscillation angles are maximal. Nor can it provide a fourth light neutrino. In this letter, we take a different approach. We assume that both the atmospheric and the solar neutrino oscillation angles are nearly maximal and investigate how this can achieved in a model with *light* right-handed neutrinos, or better known as sterile neutrinos. We discuss a scenario in which the resulting neutrino masses is naturally pseudo-Dirac and compatible with the usual hierarchical mass structure of quarks and charged lepton sectors. We will show that this scenario could be a natural consequence of a slightly broken lepton number symmetry, and naturally explains the experimental data. In addition to giving rise to the maximal mixing angles in atmospheric and solar neutrino mixings naturally, it also naturally explains by the ν_e-ν_μ mixing angle observed in the LSND experiment is close to the Cabbibo angle.

The greatest potential problem about having more sterile neutrinos lies with big bang nucleosynthesis (BBN) [10], as the latter predictions are quite sensitive to the N_ν, the effective number of neutrino species. However, as suggested in Ref. [11], the BBN bounds on mixing of neutrinos with sterile species can be considerably weakened in the presence of relatively large neutrino asymmetry. In a recent studies by Shi and Fuller [12], where a small initial neutrino asymmetry and a N_ν bound of 3.3 are assumed, the authors concluded that $\nu_\mu \longleftrightarrow \nu_s$ mixing as an explanation for the superK data is feasible provided that there is a simultaneous mixing between ν_τ with a lighter sterile neutrino $\nu_{s'}$ with mass-squared difference between 200 eV^2 and 10^4 eV^2 and a non-radiative ν_τ decay lifetime $\leq\ 10^3$ yr. Note also that the above studies was limited to the case where all active neutrinos satisfy $m_\nu \ll 1$ MeV. A complementary studies of the heavy ν_τ scenario [13] shows that the contribution of the latter to N_ν could go as far as -2 for some value of decay lifetime. Meanwhile, other authors [14] suggest that N_ν can be as high as 4.53. All these certainly suggests a generic situation with three sterile neutrinos is not definitely ruled out, while more carefully analyses have to be performed to check the BBN constraint on a specific model.

Another major problem of the pseudo-Dirac idea is the indications from recent statistical analyses of all available solar neutrino data [2] that the large mixing angle solution into a sterile neutrino is ruled out as a solution. However, as argued in Ref. [15], the Chlorine experiment result is actually in general disagreement with other experiments, and if the former is left out, maximal $\nu_e \longrightarrow \nu_s$ solution to the solar problem is constrained but still interesting. Hence, we consider the pseudo-Dirac idea still worths some attention. In fact, after the completion of our model, we realized that there has been quite some discussion in the literature about the general scenario [16], as well as some model building works. The latter includes the mirror matter model [17] and more from some other more general settings [18]. Our model has the special feature that it uses the (approximate) lepton number symmetry itself to enforce the pseudo-Dirac mass pattern and a Dirac seesaw structure for the suppressions of the dominating Dirac masses from the electroweak scale. Hence, we consider it an interesting alternative.

Pseudo-Dirac mass scheme. The generic Majorana mass matrix with three $SU(3) \times SU(2) \times U(1)$ singlet fermions, *i.e.* neutrinos, is given by

$$\begin{pmatrix} M_\nu & D \\ D^T & M \end{pmatrix} , \tag{1}$$

where M_ν and M are the lepton number violating Majorana masses of the ν_L's and ν_S's respectively, and D their Dirac masses. The popular seesaw scenario is characterized by $M_\nu \ll D \ll M$. However, here we shall adopt a different scenario and look for scheme that can naturally generate a mass matrix which is of pseudo-Dirac form by having M_ν , $M \ll D$.

The philosophy here is to generate all the small quantities through some kind of seesaw mechanism associated with a larger scales. The smallness of M_ν and M can be taken as a consequence of an approximate lepton number symmetry. When lepton number is spontaneously broken, the smallness of the associated vacuum expectation value (VEV) can be arranged naturally through the scalar seesaw mechanism [19], as we shall demonstrate below. In order to explain the smallness of D, we will have to invent new mechanism. One such mechanism called Dirac seesaw mechanism will be illustrated below.

Before we discussion the mechanism, let us first discuss how the pseudo-Dirac mass scheme fits the experimental data, and what its predictions would be. The basic idea here is motivated by the experimental indications of small mass-squared differences and near maximal mixings for $\nu_\mu \longrightarrow \nu_X$ and probably also for $\nu_\mu \longrightarrow \nu_e$, with a relatively "larger" mass-squared difference. The latter feature suggests resemblance with the familiar SM flavor structure. A pure Dirac mass contribution, as would be enforced by lepton number conservation, gives pairs of Majorana neutrino mass eigenstates of equal and opposite masses and 45^o mixings. If D, M_ν, and M were all nearly diagonal, in analogy with the quark and charged lepton mass matrices, one should be able to account for atmospheric neutrino oscillation as ν_μ into its sterile partner and account for large angle (MSW or vacuum) solar neutrino oscillation as ν_e into its sterile partner. The respective small mass differences are explained by small M_ν and M. Small Majorana mass contributions, will lift the pairwise mass degeneracy (neglecting the unphysical sign difference) and shift the mixing angles away from 45^o. Hence, each ν_L will have a nearly degenerate and maximally mixed sterile partner, while the full neutrino spectrum still follows a hierarchical pattern similar to the other SM fermion: $m_{\nu_e} \ll m_{\nu_\mu} \ll m_{\nu_\tau}$ with small family mixings. In addition, the Cabbibo size mixing observed by LSND will be explained by the flavor mixing in analogy with the regular quark sector. This is the basic picture which we consider very natural and straight forward.

Before we propose the generating mechanism for the mass matrix let us see what kind of values one needs to achieve for a satisfactory model. The LSND data prefers $\Delta m^2 = 0.2$ — $20\,\mathrm{eV}^2$ and $\sin^2 2\theta = 0.03$ — 0.001. The Super-K atmospheric neutrino data prefers $\Delta m^2 = (0.5$ — $6) \times 10^{-3}\,\mathrm{eV}^2$ and $\sin^2 2\theta > 0.82$ (90% C.L.). The solar neutrino data allows two large angle solutions: the MSW solution with $\Delta m^2 \approx 1.8 \times 10^{-5}\,\mathrm{eV}^2$ and $\sin^2 2\theta \approx 0.76$, and the vacuum oscillation solution with $\Delta m^2 \approx 6.5 \times 10^{-11}\mathrm{eV}^2$ and $\sin^2 2\theta \approx 0.75$. Taking these into account, a satisfactory spectrum of of neutrino masses may be given as follows :

	m_ν (eV)	Δm_ν (eV)	$\Delta m_\nu^2 = 2 m_\nu \Delta m_\nu$ (eV^2)
ν_e	$\sim 10^{-2}$ eV	$\sim 10^{-8}$	$\sim 10^{-10}$
ν_μ	~ 1	$\sim 10^{-3}$	$\sim 10^{-3}$
ν_τ	~ 20	$\sim 10^{-1}$	~ 1

Here, in the m_ν column, the value for m_{ν_μ} is motivated by LSND result. The other entries for m_ν are obtained by naively assuming that mass hierarchy among the Dirac masses are similar to that of the charged leptons. They should be considered only as suggestive values. In the Δm_ν^2 column, the rough value for $\Delta m_{\nu_\mu}^2$ is given by recent atmospheric neutrino oscillation data. The rough values for $\Delta m_{\nu_e}^2$ is given by recent solar neutrino data. Here we take the vacuum oscillation solution just for the illustration purpose. Note that a large range of $\Delta m_{\nu_e}^2$ is possible to account for current solar neutrino data depending on whether the mechanism is MSW or vacuum oscillation. As for ν_τ, there is no direct experimental hint on Δm_{ν_τ}. For instance, even m_{ν_τ} in the MeV range is a possibility. Much smaller value of m_{ν_τ} seems to fit more easily into a specific pattern with the rest of the neutrino spectrum. We choose in the above ratios among the Majorana masses (equivalent to the mass splittings, Δm) to be roughly the squares of that of among the charged leptons. This mass ratio pattern is inspired by a simple approximate flavor symmetry perspective [20] taken here only with the SM fermions. Note that the pattern suggests a Δm^2 of the order 1 eV between ν_τ and its sterile partner.

The above neutrino mass spectrum is presented only to give typical values in order to provide an order of magnitude estimate of various scales that will be introduced later in our mechanism. Our model will not, however, address the origin of the hierarchy down the families, but only illustrate a mechanism for achieving the pseudo-Dirac mass scheme.

Scalar potential and Higgses. To have an approximate lepton number symmetry in the neutrino sector, we introduce additional Higgs scalar(s) and demand that the lepton number be broken only spontaneously or softly. We wish to build a scheme such that the smallness of M_ν and M are due to the smallness of the corresponding lepton number breaking VEV's. The smallness of these VEV's will be in turn explained naturally by the existence of a larger scale. While we can not explain the origin of such scale, the tie between the small VEV and the larger scale is natural. If the lepton number symmetry is broken spontaneously, there will be Majoron. We have to make sure this Majoron does not have a substantial coupling to Z^0 boson in order to avoid the stringent constraints from the LEP experiment. In particular, we need to make sure the real partner of Majoron is not too light. In our scheme, M_ν arises at tree level through the VEV of a $SU(2)$ triplet Higgs $\Delta^{\alpha\beta}$, with hypercharge $Y = 1$ and lepton number $L = -2$. To avoid the LEP constraint, one can break lepton number using another Higgs boson with much larger VEV so that the Majoron effectively does not couple to Z^0 at tree level. A nice choice is another $SU(2)$ triplet T^α_β with hypercharge $Y = 0$ and lepton number $L = 2$. We will also discuss a less favorable case with T being replaced by a singlet σ, carrying the same hypercharge and lepton number. The triplet (T), however, is a better choice because the singlet (σ) will naturally couple to the singlet neutrinos (ν_S's) and give rise to large M in Eq.(1). The resulting Higgs sector of the model we consider here is close to those in Refs. [19,21–23]. Most of the result in this section could be borrowed directly from the references. As we shall see below, the model naturally gives rise to very small $M (\ll M_\nu)$.

The full scalar potential is given by

$$
\begin{aligned}
V(\phi,\Delta,T) = {}& \mu_2^2\phi^\dagger\phi + \mu_3^2\,\mathrm{tr}\,(\Delta^\dagger\Delta) + \lambda_1(\phi^\dagger\phi)^2 + \lambda_2[\mathrm{tr}\,(\Delta^\dagger\Delta)]^2 \\
& +\lambda_3\phi^\dagger\phi\,\mathrm{tr}\,(\Delta^\dagger\Delta) + \lambda_4\,\mathrm{tr}\,(\Delta^\dagger\Delta\Delta^\dagger\Delta) + \lambda_5(\phi^\dagger\Delta\Delta^\dagger\phi) \\
& +\mu_1^2\,\mathrm{tr}\,(T^\dagger T) + \zeta_1[\mathrm{tr}\,(T^\dagger T)]^2 + \zeta_2(\phi^\dagger\phi)\mathrm{tr}\,(T^\dagger T) + \zeta_3\,\mathrm{tr}\,(T^\dagger T T^\dagger T) \\
& +\zeta_4\,\mathrm{tr}\,(\phi^\dagger T T^\dagger\phi) + \zeta_5\,\mathrm{tr}\,(\Delta^\dagger\Delta)\mathrm{tr}\,(T^\dagger T) + \zeta_6\,\mathrm{tr}\,(\Delta^\dagger\Delta T^\dagger T) \\
& +\zeta_7\,\mathrm{tr}\,(\Delta^\dagger T^\dagger\Delta T) - \kappa(\phi^\alpha\phi^\beta\Delta^\dagger_{\alpha\gamma}T^\gamma_\beta + \mathrm{h.c.})\,, \qquad (2)
\end{aligned}
$$

where explicit $SU(2)$ indices are shown only for the κ-term. The singlet version has T replaced by σ. Note that the κ coupling naturally give rise to the relation among the VEV's as given by

$$
v_3 \sim \kappa v_2^2 v_T/\mu_3^2\,, \qquad (3)
$$

where v_i are defined as

$$
\begin{aligned}
\frac{v_T}{\sqrt{2}} &\equiv \langle T\rangle \quad (\text{or} \quad \langle\sigma\rangle)\,; \\
\frac{v_2}{\sqrt{2}} &\equiv \langle\phi\rangle\,; \\
\frac{v_3}{\sqrt{2}} &\equiv \langle\Delta\rangle\,. \qquad (4)
\end{aligned}
$$

The VEV's are understood to be real and lie in the directions of the neutral components. The neutral scalar mass matrix is given by

$$
\boldsymbol{M_R^2} = \begin{pmatrix}
2(\zeta_1+\zeta_3)v_T^2 + \frac{1}{2}\kappa v_2^2\frac{v_3}{v_T} & (\zeta_2+\zeta_4)v_Tv_2 - \kappa v_2v_3 & (\zeta_5+\zeta_6+\zeta_7)v_Tv_3 - \frac{1}{2}\kappa v_2^2 \\
(\zeta_2+\zeta_4)v_Tv_2 - \kappa v_2v_3 & 2\lambda_1v_2^2 & (\lambda_3+\lambda_5)v_2v_3 - \kappa v_Tv_2 \\
(\zeta_5+\zeta_6+\zeta_7)v_Tv_3 - \frac{1}{2}\kappa v_2^2 & (\lambda_3+\lambda_5)v_2v_3 - \kappa v_Tv_2 & 2(\lambda_2+\lambda_4)v_3^2 + \frac{1}{2}\kappa v_2^2\frac{v_T}{v_3}
\end{pmatrix}, \qquad (5)
$$

The neutral pseudo-scalar mass matrix is given by

$$\boldsymbol{M_I^2} = \begin{pmatrix} \frac{1}{2}\kappa v_2^2 \frac{v_3}{v_T} & \kappa v_2 v_3 & \frac{1}{2}\kappa v_2^2 \\ \kappa v_2 v_3 & 2\kappa v_T v_3 & \kappa v_T v_2 \\ \frac{1}{2}\kappa v_2^2 & \kappa v_T v_2 & \frac{1}{2}\kappa v_2^2 \frac{v_T}{v_3} \end{pmatrix} , \tag{6}$$

which has two zero mass eigenvalues, as expected. The only non-zero mass eigenvalue of $\boldsymbol{M_I^2}$ is given by

$$m_A^2 = \frac{1}{2}\kappa \frac{v_2^2 v_T^2 + v_2^2 v_3^2 + 4 v_3^2 v_T^2}{v_3 v_T} , \tag{7}$$

which would be heavy, at least around the EW scale. The massless Majoron can be made massive by introducing an explicit soft lepton number violating $\mu_T^2(TT + T^\dagger T^\dagger)$ term to the scalar potential in Eq.(2), if this is necessary to evade astrophysical or cosmological constraints. Note that the term affects the vacuum solution of V but not the form of $\boldsymbol{M_R^2}$.

With a light majoron, a small eigenvalue from $\boldsymbol{M_R^2}$ (corresponding to a light physical scalar), has to be avoided in order not to change the invisible width of the Z^0-boson decay beyond the stringent experimental bound. An alternative way of making all the scalars heavy is to impose the hierarchy $v_3 \ll v_T$. In the latter case, the majoron, as well as the potentially light scalar, will be predominantly the T^0 or σ state, which does not coupled to Z^0. A careful inspection of Eq.(5) shows the hierarchy, $v_3 \ll v_T$, is necessary in order to avoid a scalar of mass smaller than $\sim \sqrt{v_3 v_2}$. Assuming the hierarchy, Eq.(5) gives eigenvalue for the predominantly Δ^0 state of the order $\kappa v_2^2 \frac{v_T}{v_3}$, hence above EW scale. The other two eigenvalues are at least of order v_T^2 and v_2^2 respectively, with the latter corresponding to the predominantly ϕ^0 state.

Neutrino masses and model parameters. Take the μ—ν_μ family parameters. The Dirac mass D in Eq.(1) has to be suppressed relative to charged lepton mass by roughly an order of $\epsilon = m_{\nu_\mu}/m_\mu \sim 10^{-8}$. Lepton number violating Majorana entries to mass matrix in (1) contribute to the diagonal blocks, M_ν and M. Entries to M_ν come from couple of ν_L's to the scalar Δ. Here we required $v_3 \ll 10$ eV, from a v_T bound obtained below. In Ref. [19], it has been illustrated, for the case without the extra T or σ, that the scalar Δ could be naturally heavy and yet with a small VEV; in that case, the crucial term in the scalar potential is the κ term in V [Eq.(2)] with T being replaced by a heavy mass parameter. In our modified case, the same story goes with the T-VEV, v_T, playing the latter role. It can easily be shown that appropriate choice of μ_i value in V can fix the required hierarchy $v_3 \ll v_T$ without fine-tuning, as illustrated by Eq.(3). The extra scalar T, or σ, is necessary here as the κ term without the latter explicitly violates lepton number. The lepton number violating Majorana mass terms for ν_S's, being of the same dimension, would then derive divergent loop contributions ruining our neutrino mass scheme.

If the singlet scalar σ is used, it could couple directly to singlet neutrinos, the ν_S's. Unsuppressed otherwise, this will give rise to potential larger contribution than those from

$\langle\Delta\rangle$. This is one of the reasons that we consider the version with the T triplet instead more interesting. The T scalar is actually a very interesting EW triplet. Its neutral component T^0 does not couple to Z^0, helping to get around the usual constraint on a majoron from a nontrivial $SU(2)$ multiplet; while its W-boson coupling, or contribution to the precision ρ-parameter, restricts $\langle T\rangle$ to be $< 0.04\, v_2 \sim 10\,\text{GeV}$ [24]. Hence, it predicts interesting accessible phenomenology for the majoron and its real partner.

We will discuss below a Dirac-seesaw mechanism for the natural suppression of the neutrino Dirac mass scale below that of the charged leptons, without introducing particularly small Yukawa couplings. Following the idea, one can simply assume the Dirac mass generating Yukawa couplings among the leptonic-doublets and singlet neutrinos to be about the same, for each of the three families, as those of the corresponding charged leptons. If we further take the M_ν generating Yukawa couplings, those among the leptonic doublets and Δ, to be about the same as that of $\phi^\dagger$ leptonic Yukawa couplings, we would then have $\Delta m_{\nu_\mu}/m_\mu \sim v_3/v_2$; hence $v_3 \sim 10^{-11}\, v_2$. If we identify only the third family Yukawa couplings in the latter case, and assume the suppressions of the Yukawa couplings involving the Δ down the families as going as the square of thse involving $\phi^\dagger$, we would have $v_3 \sim 10^{-11}\, v_2\, \frac{m_\tau}{m_\mu}$, about an order of magnitude larger. This latter case is in accordance with assumptions used in our illustrative neutrino mass spectrum at the beginning. From Eq.(3, we have then the required scale for μ_3 to be about $10^7\,\text{GeV}$. As for v_T, $\sim 10^{-2}\, v_2$ could be a reasonable estimate.

A Dirac-seesaw mechanism. We introduce here a Dirac-seesaw mechanism to achieve at the Dirac mass suppression factor ϵ. Consider the Yukawa coupling $\bar{\nu}_S\phi^\dagger\nu_L$ to be forbidden by a Z_2 symmetry under which only ν_S transforms non-trivially. The Dirac mass term can be recovered through a dimension five term $S\,\bar{\nu}_S\phi^\dagger\nu_L$ with a VEV for the scalar S also transforming non-trivially under the Z_2 symmetry. We have then the suppression factor $\epsilon = \frac{\langle S\rangle}{M_N} \sim 10^{-8}$, where M_N corresponds to some relevant higher mass scale. For instance, if there is a vector-like pair of singlet fermions $N_L - N_R$ transforming trivially under the Z_2 symmetry with Dirac mass M_N. N_R would couple to ν_L through $\phi^\dagger$ while N_L would couple to ν_S through S. The former could be taken to be of the same order as that of the charged lepton masses, denoted by m_ℓ, with a similar heirarchy down the families. The scheme then results in a Dirac-seesaw mass matrix of the form

$$\begin{pmatrix} 0 & \langle S\rangle \\ m_\ell & M_N \end{pmatrix} .$$

Integrating out $N_L - N_R$ gives the effective Dirac mass entries, D, with the suppression as required. Note that $N_L - N_R$ here carry natural lepton numbers.

The model requires the scales v_1, v_2, μ_3 (which controls the size of the VEV v_3), $\langle S\rangle$ and M_N. For a realistic model, one may wish to reduce the number of necessary scales. The scales v_1 and v_2 are sufficiently close to each other that they can be consider as one scale.

The two intermediate scales μ_3 and $\langle S\rangle$ can also be identified with each other, with both of order $10^7 GeV$. In that case, M_N could be around GUT scale, $10^{15} GeV$. These are just typical scales that make realistic embedding of the model into a grand unification theory possible. We shall not try to provide such embedding here.

The Dirac-seesaw mechanism will not mess up with the general scheme of the model. Any Majorana mass has to arise from lepton number violating VEV(s). Consider $\langle\Delta\rangle$ and $\langle T\rangle$. They do not have direct couplings to the singlet fermions. We check that contributions to Majorana mass of the latter do not arise till at least two-loop level. Moreover, it can easily be shown that Majorana mass terms for the N_L and N_R singlets contribute to M_ν or M only with extra suppression factors $\frac{v_2}{M_N}$ and $\frac{\langle S\rangle^2}{M_N^2}$ respectively, as a result of the seesaw structure.

Moreover, the Z_2 symmetry can easily be modified to forbid the undesirable couplings giving rise to Majorana mass for the ν_S's, for instance from $\langle\sigma\rangle$. Afterall, the Z_2 symmetry is introduced here only as an explicit illustration of the Dirac-seesaw mechanism needed to suppressed the entries to D. More complicated symmetries can be used for the purpose, which may reduce the required ratio of $\frac{\langle S\rangle}{M_N}$, by making $\epsilon \sim \left(\frac{\langle S\rangle}{M_N}\right)^n$, and may be even take care of the family hierarchy itself. There are plenty of horizontal/family symmetry models of the type in the literature [25].

Conclusion. We analyzed here the scenario of three family of pseudo-Dirac neutrinos. An explicit model is presented to show how the idea could work with an extended Higgs sector and an approximate lepton number symmetry, broken spontaneously or otherwise. The T triplet version of our model promised a safe triplet majoron with interesting phenomenology. A Dirac-seesaw mechanism is introduced separately for the suppression of the Dirac masses. Higgs/majoron phenomenology and the incoporation of the Dirac seesaw into a complete horizontal symmetry model are the interesting issues to be further pursued.

Acknowledgements : O.K. thanks the National Center for Theoretical Sciences, and National Tsinghua University of Taiwan for hospitality. DC is supported by a grant from National Science Council of R.O.C. and O.K. was supported in part by the U.S. Department of Energy, under grant DE-FG02-91ER40685.

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